

# Summary of Session D1(ii), String Theory and Supergravity

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## Abstract

The talks presented in the string theory and supergravity session of the GR16 conference in Durban, South Africa are described below for the proceedings.

The strings and supergravity session featured a small but varied collection of talks ranging from studies of exact solutions and solitons to supersymmetry, cosmology, and talks related to the gauge-theory/gravity dualities of [1, 2]. Given the breadth of topics and the rather liberal amount of space made available in the proceedings, it seemed best to allow each speaker to describe their talks in some length. What follows is therefore a description of each talk in the order that they were presented. Each contribution was written by the speaker and only slightly edited by myself as session chair. For full details of the works, please refer to the references provided below.

## Reduced $D = 10$ $\mathcal{N} = 4$ Yang-Mills Theories

Matthias Staudacher

Staudacher discussed various aspects of the dimensional reductions of the maximally supersymmetric gauge theory, namely  $\mathcal{N} = 1$  in  $D = 10$  to lower dimensions, and in particular the cases  $D = 10 \rightarrow d = 0, 1, 2, 4$ . These reductions are relevant since supersymmetry survives the reduction process, allowing one to obtain a number of exact and analytic results. This is particularly important since there exist manifold, largely conjectural relationships to string theory, supermembrane quantization and supergravity models.

The first half of the talk focused on the reductions to  $d = 0, 1, 2$ . All three cases have been used in different proposals for non-perturbative definitions of string theory and M-theory, going, respectively, by the names IKKT model, deWit-Hoppe-Nicolai or BFSS model, DVV model or matrix string theory. A report was given on a number of recent results concerning the  $d=0$  reduction [3, 4]. This reduction is of interest in its own right and is also relevant to the bound state problem of the  $d = 1$  reduction. This work demonstrates that the current techniques for counting the number of ground states are not yet consistent and in fact quite incomplete. It is also relevant to the issue of computing exact partition functions in the  $d = 2$  reduction.

The second half of the talk discussed an ongoing investigation of Maldacena-Wilson loops in the  $d = 4$  gauge field theory: Using the AdS/CFT correspondence between classical supergravity and the strong coupling limit of the field theory, a number of exact results for these loops have been proposed in the literature. An important problem consists in relating these results to weakly coupled gauge theory. The first-ever two-loop perturbative calculation [5] was discussed. The first main result is that the Maldacena-Wilson loop operator is completely two-loop finite, suggesting finiteness to all orders. The second

chief result is that vertex diagrams contribute to the two-loop static potential. Previous lower order calculations in the literature found only (trivial) ladder diagrams to contribute. This indicates that, if AdS/CFT is correct, it indeed solves, at strong coupling, 't Hooft's longstanding planar diagram summation problem for this field theory.

## Rotating black holes in higher dimensions

Roberto Emparan

There are several motivations for studying General Relativity in dimensions higher than 4. In addition to allowing rich dynamics and new qualitative behavior, higher dimensions are required by most unification schemes, such as string theory. Moreover, in scenarios with large extra dimensions and a low fundamental scale there is the possibility that black holes will be produced and detected in future colliders[6]. Such black holes will generically be rotating.

Solutions describing neutral, rotating black holes in higher dimensions were found in[7]. For  $D \geq 6$  they present new qualitative features which, perhaps surprisingly, have so far attracted little attention. This is the subject of this contribution, which is based on work in progress with Rob Myers.

In  $D \geq 5$  dimensions, rotation can take place in more than one plane. However, the talk considered the case where the black hole spins in a single plane, with rotation parameter  $a \propto J/M$ . As is well known, the amount of rotation that a 4D Kerr black hole can support is limited: if the bound  $M \geq a$  is violated, a naked singularity results. As shown in[7], a similar bound appears for  $D = 5$ . However, for  $D \geq 6$  the horizon is present for arbitrary values of  $a$ . There is no extremal limit and no bound on the spin. Hence, these ultra-spinning black holes are distinctive of higher dimensions.

What is the shape of such an ultra-spinning black hole? An analysis of the proper size of the horizon reveals that the black hole is highly flattened along the directions parallel to the plane of rotation—a ‘pancaked’ horizon. Moreover, if the rotation parameter is sent to infinity (with the mass per unit area kept finite), the geometry that results is that of a black membrane. The latter is known to be classically unstable[8], so it is natural to ask whether the highly pancaked, ultra-spinning black holes will not become unstable before reaching this limit, i.e., already at finite values of  $a$ .

The local stability of 4D black holes has been established in classic work[9]. Global stability has been addressed using the area theorems (and their thermodynamic interpretation), which state that the sum of the areas of the future horizons can not decrease. As for black branes, both local and global arguments lead to the conclusion that they are unstable[8].

Both approaches should be applied to ultra-spinning black holes. While the local analysis of linear perturbations is still in progress, global thermodynamics points clearly to an instability of black holes in  $D \geq 6$  for sufficiently large values of  $a/M$ . To see this, the possible decay modes of the black hole were identified and the area of the final products were compared to that of the initial black hole for the same mass and spin. Several decay modes were studied, such as emission

of waves (modeled by a gas of null particles, or using the radiation formulas for near-Newtonian sources), or the black hole breaking apart into several smaller black holes (a classically forbidden process). In all cases the instability sets in at  $a/M \approx$  a few. Consistently, this happens only for  $D \geq 6$ ; for  $D = 4, 5$  this approach predicts no instability.

### Black hole entropy calculations based on symmetries

Jacek Wiśniewski, with Olaf Dreyer and Amit Ghosh

A microscopic derivation of black hole entropy is one of the greatest challenges to candidate quantum theories of gravity. As an alternative to the existing quantized models, a set of very attractive ideas was recently suggested by Andrew Strominger[10] and Stephen Carlip[11]. Their symmetry based approaches are very general and mostly classical. The starting point is an observation that symmetry generating vector fields of black hole space-time form a  $\text{Diff}(S^1)$  algebra which, on the level of the algebra of conserved charges associated with these vector fields, becomes a centrally extended Virasoro algebra[12]. The black hole space-time turns out to be a representative state of the algebra with a fixed conformal weight. Then, solely using representation theory, one can count the degeneracy of such a state and this gives the entropy of the black hole :  $S = 2\pi\sqrt{cH_0/6}$ . Here,  $c$  is the central extension and  $H_0$  is the conformal weight of the black hole or, more precisely, the eigenvalue of the Hamiltonian (same as the zero-mode of the Virasoro algebra) for the black hole space-time as the eigenstate.

These calculations, however, face some conceptual and technical problems. Strominger's calculations are based on *asymptotic* symmetries. It is not apparent how these symmetries capture the essence of the black hole space-time. In fact, the results are equally applicable to a star having similar asymptotic behavior. Subsequently, Carlip improved on this idea by making the symmetry analysis in the near-horizon region. Conceptually this approach is much more satisfactory in that the black hole geometry is now at the forefront. Ref.[11] also, however, faces some technical problems which corrected in[13] and some interesting results emerge :

a) The Lie brackets of the vector fields form a  $\text{Diff}(S^1)$  algebra both on and near the horizon. b) The vector fields do not admit a well-defined limit to the horizon (horizon penetrating coordinates were used to make this explicit). c) It is essential that the entire calculation of the Poisson bracket of charges (i.e., Hamiltonians of the vector fields) is performed at a distance  $\epsilon$  away from the horizon and the limit  $\epsilon \rightarrow 0$  is taken at the end. The lack of limit of the vector fields forbids a clear interpretation of the symmetries in the classical gravity. Presumably, this feature is an indication that the true origin of the central charge is quantum mechanical where  $\epsilon$  is to be regarded as a regulator.

There is in fact a whole one-parameter family of such vector fields forming  $\text{Diff}(S^1)$ , as above. As a result both  $c$  and  $H_0$  are modified, but in such a way that the entropy is always reproduced (up to a multiplicative factor of  $\sqrt{2}$ ). Only for a specific choice of this parameter, motivated by some arguments in

the Euclidean signature, one can shift  $H_0$  by some ‘ground state’ value to get rid of  $\sqrt{2}$ . However, the meaning of this choice is unclear.

Finally, one can perform a symmetry analysis completely on the horizon within the framework of *isolated horizons* (see other talks). The framework is naturally suited to address the question of symmetries of black holes in equilibrium (very weak assumptions are made). It turns out that no central extension appears in this case. Summarizing, the current viewpoint of the authors is that probably there is some truth in the symmetry based approaches, but it is hard to avoid details of quantum theory, especially in order to understand the origin of the central charge. This could be the case because one is attempting to give an essentially classical argument for a phenomenon that is inherently quantum mechanical.

### **Exact Super Black Hole Solutions**

R.B. Mann, with J. Kamnitzer and M.E. Knutt

Mann reported on a project which considered the problem of finding exact solutions to supergravity coupled to matter. Very few exact classical solutions to supergravity theories are known that have non-trivial fermionic content. A superparticle (which, if massive, is a D0-brane), a cosmological constant and a super-Liouville field were included as matter sources, each minimally coupled to  $(1+1)$ -dimensional supergravity.

One of the pitfalls of finding exact solutions is in ensuring that they cannot be reduced by infinitesimal local supersymmetry transformations to purely bosonic solutions. Working in superspace offers a straightforward means of avoiding this difficulty, since a superspace supergravity solution – one which satisfies the constraints – has nonzero torsion beyond that of flat superspace. The torsion is a supercovariant quantity, and as such its value remains unchanged under a gauge transformation. Hence any exact superspace solution with non-zero torsion must necessarily be non-trivial in this sense.

Mann reported on several exact solutions obtained for each of the supermatter sources mentioned above. The exact compensator superfield that describes the supergravity can be used to construct models of two-dimensional supersymmetric black holes with non-trivial curvature. To our knowledge these are the first solutions found using this technique. The superparticle and cosmological solutions had locally constant supercurvature[14], but the super-Liouville solution had locally non-constant curvature[15]. In the latter case possibility that a gravitini condensate formed was considered and examined the implications for the resultant spacetime structure. All such condensate solutions were found to have a condensate and/or naked curvature singularity.

### **Inverse dualisation and non-local dualities between gravity and supergravity theories**

Dmitri Gal'tsov, with Chiang-Mei Chen and Sergei A. Sharakin

Gal'tsov's talk was based on the preprint hep-th/0109151 which finds classical dualities of a new type between Einstein vacuum gravity in certain di-

mensions and ten and eleven-dimensional supergravities. The main idea is that Kaluza-Klein two-forms arising in toroidal compactification of vacuum gravity can be dualized in dimensions  $D \geq 5$  to higher rank antisymmetric forms and these forms may be identified as matter fields belonging to bosonic sectors of supergravities. While it is perhaps not surprising that the Maxwell equations and the Bianchi identities for the KK fields translate into similar equations for dual higher rank forms, a non-trivial test is whether the dilatonic exponents in the reduced actions are the same. Several cases of such dualities are described. The most interesting is the correspondence between  $2+3+6$  dimensional reduction of the eleven-dimensional supergravity and eight-dimensional Einstein gravity with two commuting Killing vectors. A related duality holds between both (suitably compactified) IIA and IIB ten-dimensional supergravities and eight-dimensional Einstein gravity with three commuting Killing vectors. Another case is the correspondence between the ten-dimensional Einstein gravity and a suitably compactified IIB theory. It is worth noting that all dualities of this sort are non-local in the sense that variables of one theory are related to variables of the dual theory not algebraically, but via solving differential equations.

A remarkable fact is that the  $11D$ -supergravity/ $8D$ -gravity duality holds not only in the bosonic sector, but also extends to Killing spinor equations exhibiting unbroken supersymmetries of the  $11D$  theory. Namely, the existence of Killing spinors in the supergravity framework is equivalent to the existence of covariantly constant spinors in the dual Einstein gravity. It would be interesting to check whether this correspondence found at the linearized level extends non-linearly, i.e. holds for suitably supersymmetrized  $8D$  gravity. A more challenging question is whether classical dualities found here have something to do with quantum theories. Although an answer was not presented in the talk, the results concerning the ten-dimensional supergravities look promising in this direction.

### **New supersymmetry algebra on gravitational interaction of Nambu-Goldstone fermion**

Motomu Tsuda, with Kazunari Shima

A supersymmetric composite unified model for spacetime and matter, superon-graviton model (SGM) based upon  $SO(10)$  super-Poincaré algebra, is proposed in the papers[16, 17]. In SGM, the fundamental entities of nature are the graviton with spin-2 and a quintet of superons with spin-1/2. The fundamental action which is the analogue of Einstein-Hilbert (E-H) action of general relativity (GR) describes the gravitational interaction of the spin 1/2 N-G fermions in Volkov-Akulov (V-A) model[18] of a nonlinear realization of supersymmetry (NL SUSY) regarded as the fundamental objects (superon-quintet) for matter.

Tsuda's talk performed the similar geometrical arguments to GR in the SGM spacetime, where the tangent Minkowski spacetime is specified by the coset space  $SL(2, \mathbb{C})$  coordinates (corresponding to N-G fermion) of NL SUSY of V-A model[18] in addition to the ordinary Lorentz  $SO(3,1)$  coordinates, and discussed the structure of the fundamental SGM action[17, 19, 20]. The overall

factor of SGM action is fixed to  $\frac{-c^3}{16\pi G}$ , which reproduces E-H action of GR in the absence of superons (matter). Also in the Riemann-flat space-time, i.e. the vierbein  $e_a^\mu(x) \rightarrow \delta_a^\mu$ , it reproduces V-A action of NL SUSY[18] with  $\kappa^{-1}V-A = \frac{c^3}{16\pi G}\Lambda$  in the first order derivative terms of the superon. Therefore our model (SGM) predicts a (small) non-zero cosmological constant, provided  $\kappa_{V-A} \sim O(1)$ , and possesses two mass scales. Furthermore it fixes the coupling constant of superon (N-G fermion) with the vacuum to  $(\frac{c^3}{16\pi G}\Lambda)^{\frac{1}{2}}$  (from the low energy theorem viewpoint), which may be relevant to the birth (of the matter and Riemann space-time) of the universe. The (spacetime) symmetry of our SGM action was also demonstrated. In particular, the commutators of the new NL SUSY transformations on gravitational interaction of N-G fermion with spin-1/2[17, 19] and -3/2[19, 21] form a closed algebra, which reveals N-G (NL SUSY) nature of fermions and the invariances at least under a generalized general coordinate and a generalized local Lorentz transformations. In order to linearize the SGM action, the linearization of  $N = 2$  V-A model which is now under investigation is extremely important from the physical point of view, for it gives a new mechanism generating a (U(1)) gauge field of the linearized (effective) theory[22].

### Quantum Cosmology from D-Branes

P. Vargas Moniz, with A. Yu. Kamenshchik

Recent developments in string theory suggest that, in a Planck length regime, the quantum fluctuations are very large so that string coupling increases and consequently the string degrees of freedom would not be the relevant ones. Instead, solitonic degrees of freedom such as D-p-branes would become more important. Hence, what would be the effect of those new physical degrees of freedom on, say, the very early universe and in particular from a quantum mechanical point of view?

In this work, one has initiated an investigation on D- $p$ -brane induced quantum cosmology. It could be pointed that it may not be justified to quantize an effective theory (arising from a fundamental quantum theory). However, in so far as new fundamental fields and effects arise from the fundamental theory, a quantization of the effective action could capture significant and relevant novel features.

The starting point is the result (obtained by Duff, Khai and Lu) that the natural metric that couples to a  $p$ -brane is the Einstein metric multiplied by the dilaton. Employing an (adequately) modified Brans-Dicke action with a deformation parameter  $p$ -dependent, different quantum cosmological scenarios were analyzed. In particular, several early universe scenarios were identified similar to quantum Pre-Big-Bang and Universe-anti-Universe creation. The possible quantum mechanical transition amplitudes were also studied with a view towards determining the effect of quantum cosmological solitons in the very early Universe. Finally, it was found that the solutions of Wheeler-DeWitt equation allowed for sub-class with  $N = 2$  SUSY. Other consequences regarding "stringy" cosmology were investigated, namely possible duality transformation

in the effective action and their relation to Pre-Post-Big-Bang scenarios. Possible developments of this work include considering D-brane realistic actions and SUSY extensions.

## **Polarization of the D0 ground state in quantum mechanics and supergravity**

Donald Marolf, with Pedro Silva

Marolf's talk addressed a quantum version of the dielectric effect described by Myers in[24]. In[24], the application of a Ramond-Ramond background field to a D0-brane system induces a classical dielectric effect and causes the D0-branes to deform into a non-commutative D2-brane. In contrast,[23] places D0-branes in the background generated by a stack of D4-branes. While no classical dielectric effect results, the four-branes modify the potential that shapes the non-abelian character of the quantum D0 bound state. As a result, the bound state is deformed, or polarized.

Two aspects of the deformation were studied and compared with the corresponding supergravity system. Fundamental to this comparison is the connection described by Polchinski[25] relating the size of the matrix theory bound state to the size of the bubble of space that is well-described by classical supergravity in the near D0-brane spacetime. The near D0-brane spacetime is obtained by taking a particular limit in which open strings decouple from closed strings. The result is a ten-dimensional spacetime with small curvature and small string coupling when one is reasonably close (though not too close) to the D0-branes. However, beyond some critical distance  $r_c$  the curvature reaches the string scale. As a result, the system beyond  $r_c$  is not adequately described by the massless fields of classical supergravity. The goal was thus to compare deformations of the non-abelian D0-brane bound state with the deformations of this bubble of 'normal' space.

While the detailed effects were beyond the scope of the work presented, the deformations of the quantum mechanics ground state and the supergravity bubble were shown to have corresponding scaling properties. This supports the idea that the gravity/gauge theory duality associated with D0-branes can be extended to include couplings to nontrivial backgrounds such as those discussed in[26, 27, 24]. A part of this was the analysis in an appendix of infrared issues associated with 't Hooft scaling in 0+1 dimensions. This in turn strengthens the argument that Polchinski's upper bound[25] on the size of the D0-brane bound state in fact gives the full scaling with  $N$ . Corresponding arguments can in fact be made for all  $Dp/D(p+4)$ -systems for  $p \leq 2$ .

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